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Effect of Pulp Drying History on Pressing and Drying

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## EFFECT OF PULP DRYING HISTORY ON PRESSING AND DRYING

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### ABSTRACT

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This paper is primarily a review and assessment of the literature relevant to understanding the effect of pulp drying history on pressing and drying (machine productivity). Several factors make water removal from paper webs formed from virgin fibers more difficult than from those using previously dried fibers. Webs from previously dried fibers have higher permeability, leading to a higher solids content after drainage. Water within the cell wall will control and limit the extent of dewatering, making the dryness after pressing lower for webs from never-dried fibers. The higher evaporation rate, lower critical moisture content and higher vapor diffusion rate will increase the drying rate for webs from previously dried fibers. It is hypothesized that these factors are closely related to the irreversible reduction in swelling of fibers and the reduction of fiber wall pore volume and size. A research approach is suggested to better understand and quantify the impact of pulp drying history on water removal.

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### INTRODUCTION

Paper mills can be broadly classified as either integrated (with their own pulp supply) or nonintegrated. In integrated mills, pulp is usually stored at 10-14% consistency before use on the paper machine. The pulp to be used for nonintegrated operation must be further dewatered to decrease transportation costs. In many instances, it is necessary to dry the pulp web prior to shipment. Pulp deliveries are commonly made at 90-95% air dry in the form of baled dry lap sheets. Besides baled pulp, recycled fiber use is increasing rapidly in the world. These two kinds of previously dried pulp comprise a significant portion of the overall pulp requirement for paper and paperboard production.

Papermakers often find that it is more difficult to remove water from paper webs formed from virgin fibers than from those formed from previously dried fibers. Therefore, the machine has to slow down or the dryer section has to be operated at higher temperatures when virgin fiber is used. Although this phenomenon has been known for a long time, there are no complete explanations in the literature.

During the papermaking process, water is removed by drainage and vacuum in the forming section, by mechanical forces in the press section, and by evaporation and vapor transport in the drying section. Any fiber and web characteristics altered by the fiber drying history could affect the water removal in these three processes. Therefore, a systematic investigation, focusing on fundamental mechanisms, is needed to understand how the fiber drying history affects the water removal during these processes. A better understanding of these effects, and their relative importance, would help to reveal ways to overcome the water-removal limitations associated with use of virgin fibers. In simplest terms, it is of interest to know whether it is the increased water load to the dryer section or a reduced drying rate in the dryer section, itself, that is most important.

In this paper, we first review the relevant literature and discuss the potentially important phenomena involved in the problem. Then, hypotheses are postulated to explain the possible mechanisms that lead to the different water-removal properties associated with virgin fibers and previously dried fibers. Finally, a research approach is proposed (but not yet implemented) that will provide the data needed to both quantify the impact of pulp drying history on water removal and explain the dominant mechanisms.

## LITERATURE REVIEW

A review of literature in several subject areas, ranging from the fiber level to the paper-machine level, believed to be relevant to understanding the key issues regarding the effect of pulp drying history on water removal, is presented in this section. Additional references will be discussed in later sections, in the context of problem analysis and suggested future research.

### Fiber Wall Structure

The cell wall of a wood fiber is a lamellar structure; following chemical and mechanical treatments, it can be observed in the wet state to be in a delaminated condition. Early optical microscopy published by Bailey [1] showed that the wall can be subdivided into 20 to 40 perfectly concentric and spaced lamellae. Page and De Grace [2] reported from two to 15 lamellae in the wall — the numbers increasing with the extent of beating. Stone and Scallan [3] claimed that the structure of the wood-fiber cell wall consists of concentric lamellae only one microfibril thick, separated by layers of a lignin-hemicellulose gel. Chemical pulping progressively removes this interstitial gel, although some reaggregation takes place toward the end of pulping. It is claimed that the wet cell wall of a low-yield pulp still contains up to several hundred separated lamellae, each only a few microfibrils thick.

The widely accepted lamellae structure model was first proposed by Scallan [4] in 1974. In this model, Scallan considered a low-yield pulp fiber to be comprised solely of cellulose microfibrils. The microfibrils are quadrilateral in cross section, and the sides are oriented parallel to the cell wall, corresponding to the hydroxyl-rich 101 planes of the crystal lattice. A dried fiber wall was shown to be essentially nonporous and to have a density close to that of the crystal lattice. It has also been shown that in this dry state there are no hydroxyl groups that are not engaged in hydrogen bonding. Therefore, it would appear that in the dried state, the microfibrils are bonded together in a close-packed array.

During rewetting of this dry structure, water will enter the more accessible 101 plane, which is less regularly bonded, and tangentially oriented planes between the microfibrils. Since water is a polar reagent, it will break and reform hydrogen bonds, leading to the delamination of the wall upon swelling.

However, the entry of water is not limited to the tangential spaces between microfibrils. Therefore, accompanying tangential cleavage, there would be a proportional cleavage of radially oriented bonds, although to a lesser degree. With further swelling and the breakage of all tangential bonds, the wall will become concentrically delaminated.

### Fiber-Water Interaction

**Water classification.** In the literature, the water in wet pulps has been classified in different ways [5-10]. Usually, water of three types can be detected in a saturated wet fiber. These have been named water of constitution, imbibed water, and free water [5].

Water of constitution is that which remains at zero relative vapor pressure. It is water held by fairly strong valence bonds, probably hydrogen bonds. It has abnormally high density, so it does not act as a solvent, does not react to humidity changes, and appears to be in a solid state. It is suggested that this water forms a monolayer on the cellulose surface. The amount existing in this state varies from source to source but is probably less than 1% bone dry basis fiber weight.

Imbibed water is all the water that is held by the fiber wall. The actual state occupied by this type of water is not clear, but Christensen and Giertz [9] suggest it forms additional layers on top of the basic monolayer. The amount of water in the imbibed state again varies but is usually on the order of 30% to 60% bone dry basis.

Free water is that held by the fiber after fiber saturation has occurred. This is held by capillary forces and is not bonded in any way. The amount of free water held by a fiber depends upon the degree of beating of the fiber and the nature of the lumen. The amount of free water held may be as high as 200% bone dry basis.

Stone and Scallan [7] have further classified imbibed water. They distinguished between water existing in the wall material itself (the sites on which the water is held are termed microreticular pores) and water existing in the pore cell wall (which are termed macroreticular pores). They have investigated the existence of these two forms of water and found that they existed continuously in a 1 to 4 ratio, micro to macro, over the moisture content range 0-5% bone dry basis.

The terms intra-wall and inter-wall water are also used in the literature [8]. Intra-wall water means the water located in the cell wall, while inter-wall water indicates the water between the fibers and in the lumen. The intra-wall water can also be divided into specific hydration water and into nonassociated water. The specific hydration water in cellulose is dependent only on the fraction of accessible cellulose and is attached to the cellulose by relatively strong bonds. This specific hydration water is thus expected to be more difficult to remove than the rest of the intra-wall water.

**Fiber saturation point (FSP) and water retention value (WRV).** In 1906, Tiemann introduced the term “fiber saturation point” to refer to the moisture of the water-saturated cell walls of wood fibers [11]. The term has since been extended to wood pulp fibers, cotton, and other natural cellulose fibers and to the moisture content of water-saturated fibers prepared from regenerated cellulose. FSP is a fundamental property of wet cellulose fibers. Unfortunately, although use of the solute exclusion technique [3] is a conceptually simple way to measure the fiber saturation point, it is time-consuming and requires expensive equipment and experimental precision.

Many years before the development of the solute exclusion technique to measure the fiber saturation point, a technique was developed to determine what has been termed “the affinity of cellulose for water” [12]. In this procedure, a wet fibrous sample is centrifuged in such a way that water can be driven out of the sample. After centrifuging under standard conditions of centrifugal force and time, the moisture content of the sample is reduced to a value that has been called the “water retention value” (WRV). The technique originated with workers on textile fibers but was applied to pulp fibers by Jayme and co-workers [12]. Like the fiber saturation point, the water retention value of the pulp is also affected by the pulping process and pulp yields, the degree of beating, drying and rewetting, and treatments with swelling agents.

The amount of water retained by a pulp will decrease with increasing applied centrifugal force, and it is obvious that at some stage the moisture content will pass through a value corresponding to the fiber saturation point. However, by comparing the water retention values of a number of pulps with fiber saturation point determined by the solute exclusion method, it has been shown that the centrifugal technique has provided a close estimate of the fiber saturation point. Under certain conditions, i.e., the application of centrifugal forces of 900 g for 30 minutes, the water retention value is an “exact” measure of the fiber saturation point for values up to 1.80 gram of water per gram of solids [13]. This method has been standardized and has become a rapid and simple method of determining the fundamental parameter, the fiber saturation point, of most chemical pulps of commercial interest.

**Fiber swelling.** In the wet web, water is present both in capillary voids between the fibers and in the porous structure of the fiber wall. The amount of water held by the fiber (can be called swelling water or intra-wall water) depends on the kind of pulp, on the degree of beating, and on the chemical environment [14]. A slightly swollen pulp such as a coarse mechanical pulp may contain about 1 gram of water per gram of cellulose, whereas a highly swollen pulp such as a beaten unbleached kraft pulp may contain about 2.5 grams of water per gram of cellulose. The swollen fiber contains water in pores of different diameters, the largest being about 50 nm.

A mat of swollen fibers is a rather inhomogeneous structure. When the fiber mat is subjected to pressure, stresses are concentrated at the contact areas between the fibers, especially at the fiber crossings. Water is thus preferentially expelled from the fibers at these points of high local pressure, and the solids content varies along the fiber length. Consequently, water is expected to be squeezed out from some regions of the fiber wall at a mean solids content below that corresponding to swelling of the fiber. On the other hand, some of the voids between the fibers are still filled with water at a solids content corresponding to the fiber saturation point. The swelling is also inhomogeneous and varies along a single fiber, depending on, for example, the kind of mechanical treatment (e.g., beating) to which the pulp has been subjected.

It is reasonable to expect that the removal of swelling water is a slower process than the removal of water from the interstices between the fibers. In presses where the pressure impulse is limited, it would, therefore, be expected that the solids content obtained would be related to the swelling of the pulp. Such correlation has also been reported [16, 17]. The WRV value seems to be able to predict the solids content after the presses. Therefore, the removal of swelling water appears to be a limiting factor for the attainment of a high solids content after the presses.

**Permeability.** Permeability data reflects the resistance to flow in the transport channels between the fibers in the wet web. This permeability of pulp fiber mats is important for the evaluation of many pulping and papermaking processes such as washing, dewatering, and wet pressing.

The physics of flow through porous media was surveyed by Scheidegger [18]. The pressure drop over a porous bed is influenced partly by energy losses due to the viscous drag of the fluid in the pores, partly by inertial losses due to turbulent eddies and repeated changes in direction of flow in the narrow channels. In case of low velocities, the inertial

losses are negligible. The flow can then be considered as viscous and is described by Darcy's law, which will be used later in this paper.

Systematic investigation of the permeability of pulp fiber mats at solids contents in the 25-45% interval are scarce in the literature. Although the literature data are difficult to compare directly, it can be noted that the permeability data reported by different authors differ by several orders of magnitude [19-21]. Carlsson [20] measured the permeability for a number of pulps treated in different ways and wet pressed to different solids contents. The experiments show that the beating of chemical pulps or mechanical pulps as well as increasing dryness decreases the permeability coefficient. He also found that low-yield kraft pulps exhibited lower permeability coefficients than high-yield kraft pulps, especially when the pulps had been beaten.

There are no data available directly comparing previously dried and never-dried pulp permeabilities. However, Carlsson [20] found that electrolyte concentration had a different effect on the permeability for different pulp. An electrolyte concentration of 0.5 M NaCl did not significantly affect the permeability coefficient of the bleached sulfate pulp. However, for holocellulose pulp, the permeability coefficient increased with increasing electrolyte concentration [20].

### Effect of Drying History on Fiber Properties

**Change of fiber dimension.** When drying, wood pulp fibers undergo changes that have important implications to the functional properties of the paper product. An easily visible effect of water-fiber interaction is the shrinkage of fibers due to the removal of water. It is evident that shrinkage due to drying can be substantial in the cross-section direction, but it is not significant in the fiber axial direction [22].

Nanko, et al. [23] showed through microscopic observation that shrinkage occurs after a sharp transition at high dryness level rather than gradually with decreasing moisture content. This transition is called the fiber collapse point. When comparing the shrinkage pattern of virgin and recycled fibers, Paulapuro [24] found that recycled fiber shrinks more gradually with the removal of water. Shrinkage of virgin fibers starts at a higher moisture content. A steep decline in fiber dimension is therefore typical for virgin fiber.

Based on the fiber thickness values (Table I) and visual appearance, Kibblewhite [25] found that dried and rewetted fibers are clearly more collapsed than those in the corresponding undried pulps. Fiber thickness and fiber wall thickness are significantly reduced by pulp drying, whereas fiber widths are unchanged [25].

Table I. Cross-section dimension of undried and dried and rewetted radiata pine kraft fibers [25].

Pulp treatment	Fiber thickness ( $\mu\text{m}$ )	Fiber width ( $\mu\text{m}$ )	Fiber wall thickness ( $\mu\text{m}$ )
1. Undried	21.6	44.4	4.0
1. Dried and rewetted	11.4	44.3	3.1
2. Undried	24.4	45.3	4.7
2. Dried and rewetted	15.9	44.1	4.3

Weise and Paulapuro [26] investigated the effect of multiple cycles of fiber drying and rewetting on fiber swelling. They interpreted their data as showing that the loss in reswelling is due to submorphological changes in the cell wall.

**Effect of drying on WRV and fiber swelling.** Many experiments have been conducted to examine the effect of drying history and drying conditions on water retention value and fiber swelling. This is relevant not only to recycling of paper but also to the use of previously dried market pulps, which in some respects can be considered recycled or re-used. Jayme [27], for example, investigated the effect of pulp drying and showed that a drop in WRV can be observed after drying at 70°C. Treiber and Abrahamson [28] noted a considerable drop in the fiber saturation point when drying a dissolving pulp at 120°C compared to 25°C. Okayama et al. [29] dried both shredded pulp and standard handsheets using a variety of techniques including freeze drying and microwave drying and found that each technique produced its own distinct effect on the WRV of the recycled pulp. Pycraft and Howarth demonstrated that the drying cylinder temperature on a pilot paper machine affected the recycle potential [30].

Lundberg and de Ruvo [31] noted that an increased drying temperature during the drying of Formette Dynamique-prepared sheets gave rise to reduced swelling. Restrained drying reduced the swelling even more. They used a commercial never-dried bleached kraft, with drying at 20°C and 120°C. Lundberg and de Ruvo noted that pulp prepared from paper dried at higher temperature could not regain the WRV of the initial pulp even after prolonged beating. The mechanism that they proposed to explain this is as follows. They noted first the conclusion of Stone and Scallan [32], i.e., that it is the larger pores in a fiber that preferentially close up during drying. These workers suggested that drying forces may lead to some sort of plastic flow at the crack interface resulting in strain hardening of the fiber. Lundberg also suggested that reorientation of microfibrils and better alignment of carbohydrate chains then take place, together resulting in a more intensely bonded structure eliminating the flaw in the fiber wall. They call this a "crack healing" process. In subsequent beating, this part of the cell wall stays resistant to delamination, and indeed the whole fiber becomes stiffer and perhaps more brittle. This may correspond to the observation of Bugajer [33] that multiple recycling of kraft paper leads to an increase in cellulose crystallinity while also giving rise to a reduction in swelling and interfiber bonding.

**Hornification.** As stated above, after drying, the swelling capacity of fibers is lost, and irreversibility of their swelling property is increased with the level and duration of drying. This irreversible fiber swelling property is called the loss in flexibility of wet pulp fibers, or "hornification." The effect of drying on high-yield mechanical pulp fibers is minor. However, low-yield chemical pulp fibers show a greater loss in recovery of swelling with drying. There are several mechanisms responsible for this phenomenon, although it has been a long debate and is not resolved satisfactorily yet. These mechanisms are reviewed in the following sub-sections.

**Irreversible pore closure.** The irreversible change of cellulosic cell walls upon exposure to drying has historically been attributed to the closure of pores and cracks [3, 15, 34]. Thode, et al. [34] reported that hornification is caused by the irreversible closing of micropores and cracks during drying.

Stone and Scallan [3, 15] carried out comprehensive studies on the effect of drying on the structure of the cell wall. Solute exclusion was used in characterization of the structural changes in the cell wall. It was observed that the large and intermediate size pores were reduced upon drying. This concept was also discussed by Jayme and Hunger [35]. Hornification was defined, by both groups, as irreversible changes in the capillary system of the fiber cell wall. However, many questions remain still unanswered in the area of fiber science. For example, no explanation is offered as to why the cell wall pores are lost and do not open again when the fibers are rewetted [31]. The effect of wood components, such as hemicelluloses, in the closing up of the pores was not detailed comprehensively.

**Crosslinking.** The auto-crosslinking hypothesis, as an origin of fiber hornification during recycling, was supported by several workers. Back and his co-workers [36,37] believe that natural aging or heating in an acid environment of the paper mainly promotes a hemiacetal-type crosslinking between cellulose and hemicellulose chains. Such bonds can restrict the swelling and make the fibers brittle.

**Cellulose chain cleavage.** Paper acidity, which may be present in papers because of the processes or chemicals used in their manufacture, is a major factor in the hydrolysis of cellulose. Acid penetrates the open amorphous regions of the fiber and cuts the carbon-oxygen glycosidic bonds that link the glucose units in the cellulose chain [38]. Oxidation, a reaction between oxygen and the cellulose unit, can break carbon-hydrogen bonds, as well as carbon-oxygen bonds [39]. These reactions simultaneously remove the portion of the fiber plasticized by humidity, lower the overall degree of polymerization, and make the fiber more fragile and more susceptible to breakage during subsequent beating. McComb and Williams concluded that recycled fibers from alkaline paper behave more like virgin paper and can make better recycled products [38].

Other factors have been observed to influence chain cleavage. Burgess [40] reported that tap water or calcium sulfate washed fibers exhibited less degradation after accelerated thermal aging than distilled-deionized water washed fibers. However, it is not certain to what extent chain cleavage of cellulose contributes to the embrittlement of fibers at regular conditions of commercial recycling.

**Reorganization in the fiber (cell) wall.** Upon drying, bonding forces are sufficiently large and regular to unite two or more crystalline regions as one, thus resulting in a swelling restriction in dried fibers. Clark [41] suggested that, when the fiber is dried, adjacent surfaces of cellulose and hemicellulose, previously separated, may come together. If parts of the areas coming into direct contact match sufficiently well in composition and orientation, they could form additional crystallite zones and consequently restrict swelling when rewetting.

**Hemicellulose-loss effect.** The role of hemicellulose in the manufacture of strong paper sheets has been known to papermakers for a long time. The precipitation of hemicellulose on the pulp fiber surface in the final stages of alkaline

cooking improves the paper-forming properties of fibers. Thus, some authors attributed deactivation of the fiber surface to the loss of hemicelluloses from the fiber surface.

Eastwood and Clarke [42] proposed that the effects of recycling on the flexibility and surface condition of fibers is possibly brought about by loss in hemicellulose. They determined the loss of hemicelluloses quantitatively and considered them as an indicator for loss in fiber flexibility. Nevertheless, their results were not conclusive because of the complicated behavior of hemicellulose in the strength development of paper.

### **The Effect of Pulp Drying History on Pressing and Drying**

Systematic investigations about the effect of pulp drying history on the water removal during the pressing and drying process are scarce in the literature. However, it is known that paper manufactured from rewetted pulp is more easily wet pressed and dried.

Klungness [43] compared the dewatering of never-dried kraft pulp and machine-dried pulp and found drying the pulp resulted in a web with good drainage characteristics. The average effect of using previously dried versus never-dried pulp was to increase the solids off the wire by 10.9%. But since it was easier to remove water from the never-dried pulp during pressing, the net effect of using previously dried pulp was an increase in solids to the dryers of 2.8%. The explanation for the better drainage is that the dried pulp has less specific surface area than never-dried pulp, resulting in reduced drainage resistance. This same previously dried fiber has more resistance to compression in the press or greater degree of springback after the pressing, thus leads to more rewetting than never-dried fiber. Heller [44] also found that pulp fibers that had been dried exhibited less resistance to dewatering than never-dried fibers and showed little press speed dependence. Woodward [45] reported recycled fibers from chemical processing are stiffer and swell less than those from virgin fiber. When making paper with recycled fiber, there will be an increased water removal at the press section and an increased drying rate, because recycled fibers have lower water-holding capacity than virgin fibers.

Robertson [46] found that constant rate drying for never-dried fibers terminates in the range of 20–30% solids and shows a second transition between 35 and 45%, while previously dried fibers show constant rate drying up to the 35–45% region.

Schweizer and Samer [47] compared the dewatering behavior of never-dried and previously dried pulps using both laboratory and on-machine trials. They found mechanical dewatering was better (higher post-pressing solids) with previously dried pulp as stock; an increase of 20% in machine speed was found to be possible.

## **PROBLEM ANALYSIS AND HYPOTHESES**

The objective of this section is to analyze the physical reasons for the greater difficulty in removing water from paper webs formed from virgin fibers than from those formed from previously dried fibers. It is clear from the surveyed literature that water removal during the papermaking process involves three successive processes (forming, pressing, and drying) that could be influenced by fiber drying history.

In this section, we first analyze the possible factors with emphasis on the different fiber-water interactions between never-dried fibers and previously dried fibers. Based on the analysis, hypotheses are proposed to explain the phenomena. In the next section, an experimental approach is suggested to quantify the impact of pulp drying history on water removal and to test the proposed hypotheses.

### **Forming Section**

Forming of the paper sheet is essentially a hydro-mechanical filtration process. During drainage on a Fourdrinier table, a definite boundary exists between the fiber mat that has been deposited on the wire and the pulp suspension lying above it. While the concentration of this upper layer is usually that of the headbox, drainage elements, such as table rolls and foils, may increase it slightly. The filtration characteristics of sheet formation on twin-wire machines are even more pronounced and approximate a constant pressure filtration process.

Water flow in this filtration process can be described by Darcy's law:



$$Q = \frac{KA\Delta p}{\mu L} \quad (1)$$

where  $Q$  is volumetric flow rate,  $K$  is permeability,  $A$  is flow area,  $\Delta p/L$  is pressure gradient, and  $\mu$  is viscosity. When this equation is modified to take account of the fact that liquid can only flow through the void fraction  $(1 - vc)$  of the filtration medium and that the internal surfaces of the medium will exert a drag on the fluid flow, it takes the form:

$$Q = \frac{(1 - vc)^3}{k(vc)^2 S_0^2} \frac{1}{\mu} \frac{A\Delta p}{L} \quad (2)$$

Here,  $v$  is the specific volume of the filtrate bed material,  $c$  is the concentration of fibers in the web, and  $S_0$  is the specific surface of solids. The more precise form of Darcy's equation is known as the Kozeny-Carman equation and the term ' $k$ ' is the Kozeny constant. The proportionality constant ' $K$ ', given by:

$$K = \frac{(1 - vc)^3}{k(vc)^2 S_0^2} \quad (3)$$

is the specific permeability.

Equations (2) and (3) imply that the drainage resistance is determined by: 1) the surface area of the fiber material, 2) the volume occupied by the fibers, and 3) the apparent density of the fiber.

There are few, if any, data available in the literature comparing the permeability of webs from previously dried fiber and never-dried fiber. However, if we know how the fiber drying influences the above three factors, which determine the permeability of the fiber mat, we will get some useful insight.

It is clear from the literature review that drying causes pore closure and leads to an irreversible reduction in the swelling ability of cellulose. Several investigators have shown that the swelling ability of a dried pulp is lower than that of a never-dried pulp. It may be expected that the fiber surface area exposed to water will decrease with the decrease of fiber swelling. Therefore, previously dried fiber will have a smaller surface area than that of never-dried fiber. Klungness also observed similar phenomena [43].

As we have already explained, dried and rewetted fibers are clearly more collapsed than those in the corresponding undried pulps; fiber thickness and fiber wall thickness are significantly reduced by pulp drying [25]. It is obvious this will lead to an increase of apparent density for previously dried fiber. On the other hand, the increasing of apparent density will reduce the volume occupied by the fiber for a fiber mat with a fixed volume and consistency. When comparing never-dried fiber mats with previously dried fiber mats, one will find that previously dried fiber mats have a higher void volume for filtration.

Table II gives the comparison of each term in the permeability equation between previously dried fiber and never-dried fiber. It shows clearly that previously dried fiber will have a higher permeability than that of never-dried fiber.

Table II. Comparing the specific permeability of previously dried fiber webs and never-dried fiber webs.

Term in equation	Physical mean	Previously dried fiber	Never-dried fiber
$S_0$	Surface area of fiber	Low	High
$(1 - vc)$	Void volume fraction	High	Low
$1/v$	Fiber apparent density	High	Low
$K = \frac{(1 - vc)^3}{k(vc)^2 S_0^2}$	Specific permeability	High	Low

The direct result of higher permeability of previously dried fiber is that its drainage ability will increase. With an increasing drainage ability, one can expect that the solids off the wire for previously dried fiber will be higher than that of never-dried fiber. This has been proven by experiments on a Fourdrinier paper machine [43]. Klunness [43] reported that drying the pulp resulted in a web with good drainage characteristics. The average effect of using previously dried pulp was to increase the solids off the wire by 10.9% [43].

Different off-wire solids will result in different water loads going to the press section. Ingoing sheet dryness is known to have a large effect on the outgoing sheet dryness. Smart [48] reported results of pilot machine testing using a 66 g/m<sup>2</sup> kraft sheet at 610 m/min at a second press condition. At 35% to 40% dryness level, a near linear relation of approximately 1 percentage point change in outgoing dryness was found for each 2 percentage points change in ingoing dryness. Busker [49] reported the effects of ingoing dryness over a broad range of 24% to 38% and found the outgoing sheet dryness was changed by as much as 5 percentage points through that range. These values are typical of the range of values usually found — (2–3) : 1 change in ingoing to outgoing dryness.

Based on the above analysis, we can conclude that fiber swelling ability will influence its permeability and drainage ability, which will lead to a different solids off the wire and also give a different dryness after the press section. Since previously dried fiber will swell less than never-dried fiber in water, this should result in a higher solids content than that of never-dried fiber after pressing.

### Press Section

In the previous section, we have analyzed the effect of water load to the nip on the outgoing dryness. The relationship between the change of ingoing and outgoing dryness is only suitable for the same pulp. Therefore, it is not necessarily true for pulps with different drying histories because of their different water-removal efficiency at the press. In this section, we evaluate the different pressability between previously dried fiber and never-dried fiber and analyze the possible reasons for the difference. In order to avoid confusion, and isolate the pressing effects, all of the analyses will be based on the assumption that previously dried fiber and never-dried fiber have the same solids content before pressing.

Several authors have compiled lists of factors believed to influence the water removal during wet pressing. Robertson [50] presented a diagram in 1976 of 10 variables. DeCrosta [51] compiled a diagram that includes nearly 40 possible variables. However, most of these variables concerned in the literature are related to the pressing unit operations, such as felt rewetting, dwell time, nip pressure, temperature, felt design, roll cover design, etc. There is no doubt that all of these factors will influence the water removal during pressing. While comparing the water removal of never-dried fiber with that of previously dried fiber, however, we can assume the effect of these unit operation variables on these two kinds of fibers is the same. What we should investigate here is the different water-removal ability between previously dried fiber and never-dried fiber under the same pressing condition.

**Effect of permeability.** As we have discussed, the permeability of a web from previously dried fiber is higher than that for one from never-dried fiber. Since water flows out of the web under pressure during pressing, the first point that comes to mind is that flow resistance will affect the water-removal rate, which should be related to the fiber web permeability.

Some researchers reported the effect of refining on the water removal during pressing. Anderson and Back [52] showed a change of over 7% of dryness on an unbleached kraft sheet when refined from 680 mL CSF to 340 mL CSF. Caulfield, et al. [53] reported a difference in dryness for a hardwood kraft furnish of 5 to 7% when refined from 620 mL to 350 mL CSF. Busker [49] found a change of about 15% dryness at typical wet press conditions on a bleached kraft sheet when refined from 720 mL to 200 mL CSF. Since the permeability and drainability will reduce after refining, it seems that increasing the permeability will lead to the increasing of water removal by pressing.

Upon further literature searching, however, it is found that this hypothesis may not be true. Pulp with high water-removal resistance does not dewater easily in the ingoing nip, but the high flow resistance of the sheet also does not allow a return of the water in the expanding nip. It has been found that two furnishes having the same CSF can differ in outgoing dryness by as much as 10 or 15% after undergoing a constant press condition [16]. Carlsson [20] found that the fiber web permeability has no relation to its water retention value. Since WRV is closely related to the web outgoing dryness, there may not be a clear correlation between the permeability and outgoing dryness.

**Effect of water retention value and fiber saturation point.** In a saturated web of fibers, water is located in the interstices between fibers, in the fiber lumens, and in the porous structure of the fiber wall. One intuitively understands that, on pressing a web, the first water to be displaced from the web is the portion that is squeezed from

the spaces between the fibers. However, it is not obvious at what stage water is forced from the other locations and to what extent this occurs. Since previously dried and never-dried fiber have different portions of intra-wall water and inter-wall water, it is necessary to understand how both intra-water and inter-water are removed during wet pressing. The earliest literature refers to the water removed by commercial presses as flowing exclusively from the spaces formed by the network of fibers [54]. More recent works suggest that some water is also expressed from the fiber wall [55,56].

By using a solute exclusion technique, Laivins and Scallan [56] quantitatively separated the water pressed from a pulp mat into two fractions — that expressed from the porous structure of the cell wall and that expressed from spaces between fibers. Water from both locations begins to be expressed from the mat at low pressure. However, almost all of the water between fibers (and in the lumen) is removed at pressures below 2 MPa (300 psi).

It is clear from data in [56] that the water retained in a mat pressed to beyond 2.0 MPa is predominantly within the fiber walls, indicating that it is this water rather than the interfiber water that limits dewatering. Laivins and Scallan also found that the water content after pressing is closely related to the initial level of swelling of water-swollen fibers, i.e., by the fiber-saturation point. The water remaining in the pressed mat is a constant fraction of the fiber saturation point. The proportionality was obtained from measurements at the highest pressure. However, comparable linear relationships passing through the origin exist at low pressure if the pressure is high enough to collapse the fiber and remove most of the water between the fiber.

The above analysis was based on a laboratory study and static pressing. These conditions are very different from those used in commercial presses. However, Busker and Cronin [16] examined water removal from sheets using the more practical conditions of a two-roll press standardized to a realistic load, speed, and sheet grammage. When a variety of pulps were evaluated under their pressing conditions, a correlation was found between the dryness of the sheets exiting from the press and water retention values of the pulps.

At this point, we have shown that the water content of the sheet after pressing is related closely to the water retention value or fiber saturation point. The water within the cell wall will control and limit the extent of dewatering in a press. Since the fiber will reduce its re-swelling ability and water retention value after drying, we can expect that never-dried fiber will remain at a higher moisture content than that of previously dried fiber after pressing.

## Dryer Section

Drying within paper is found to follow a complex sequence. The moisture movement in the sheet can be represented by an evaporation – diffusion – condensation cycle model [57]. In this model, the overall evaporation rate from the open surface is made up of three components: evaporation from the hot surface, evaporation from the body of the sheet due to heat supplied by conduction and condensation, and evaporation from the open surface due to the air stream. Water that is evaporated at both surfaces is replaced by capillary flow from areas of higher moisture content. Thus, there is a flow of water from the center to both sides. Cowan also concluded that the critical moisture content occurs when the closed sheet surface becomes completely dry [57].

Therefore, the drying rate of paper sheets is related to the evaporation rate, the diffusion of water in the sheet, and critical moisture content. In this section, we will compare the drying rates for previously dried fiber and never-dried fiber and analyze how these factors affect the drying rate. Again, all the analysis is based on the assumption that the initial moisture contents for the previously dried fiber web and the never-dried fiber web are the same.

**Evaporation (mass transfer) rate.** At the sheet surface, the evaporation rate can be described by the mass transfer equation:

$$M = \beta \cdot M_v \frac{(P_p - P_1)}{RT} \quad (4)$$

From equation (4), it can be seen that the water vapor pressure at the paper surface will affect the evaporation rate. The evaporation rate will increase with the increasing of vapor pressure.

It is well known that, at the same humidity, the equilibrium moisture content of pulp that has never previously been dried is higher than that of rewetted pulp because, during drying of this pulp, the smaller pores are irreversibly closed and thereafter are no longer available for the entry of water during subsequent rewetting. Since the equilibrium moisture content increases with increasing humidity (which is the ratio of vapor pressure at the pulp surface to the

saturation pressure at the same temperature), the vapor pressure for previously dried fiber will be higher than that of never-dried if their moisture content is the same. This was proven by Prahl in 1968 [58].

From the above analysis, it can be shown that previously dried fiber webs will have a higher evaporation rate than that of never-dried fiber webs under the same temperature and same moisture content. Furthermore, if we analyze this problem based on the energy requirement for evaporation, we can draw the same conclusion. Because of the pore closure of previously dried fibers, the pore volume of a previously dried fiber will be less than that of a never-dried fiber. This will lead to a higher portion of bound water in the never-dried fiber. Because there is a higher energy requirement for evaporation of bound water [58], the drying rate will decrease for never-dried fiber under the same energy supply condition.

**Critical moisture content.** The critical moisture content is defined as the moisture content when the falling rate drying period appears. In this stage free water is no longer available at the surface of the sheet. Some of the larger pores in the sheet are empty of water, and the effective area for mass transfer is reduced.

Because the dried fiber has more free water than never-dried fiber under the same moisture content, the appearing of the falling rate period will be later than that of never-dried fiber under the same drying condition. Roberson has reported that previously dried fiber shows lower critical moisture content than that of never-dried fiber [39]. Since the drying rate will decrease significantly after reaching the critical moisture content, we can expect that the overall drying rate will decrease if the fiber has a higher critical moisture content.

**Water diffusion.** During the drying process, water will flow from inside the web towards both faces. This liquid movement was confirmed by both the moisture distribution and the dye migration study by Dreshfield [59]. The dye migration data indicated a maximum dye concentration at the surface and a minimum at a point corresponding to maximum moisture content. This supported the idea that water is being supplied to the surface, where it is evaporated.

The diffusion of water in the web can still be described by Darcy's law, but we should consider the liquid phase in the web:

$$Q = k_l \frac{KA\Delta p}{\mu L} \quad (5)$$

where  $k_l$  is the relative permeability of liquid that is dependent on the degree of saturation;  $K = \frac{(1 - vc)^3}{k(vc)^2 S_0^2}$ , which is the single-phase permeability.

The driving force ( $\Delta p$ ) for water flow in this equation is not caused by mechanical pressure. It is caused by a gradient in capillary pressure that can be expressed by the Kelvin equation:

$$P_c = P_g - P_l = 2\gamma/r \quad (6)$$

where  $P_c$  is the capillary pressure,  $P_g$  and  $P_l$  are the gas and liquid pressures across the meniscus,  $\gamma$  is the surface tension of liquid, and  $r$  is the radius of curvature of the surface, which is approximately the same as the radius of the pore where the meniscus is located.

As we have stated earlier, previously dried fiber webs have a higher permeability than do never-dried fiber webs. From equation (5), it appears that the liquid diffusion rate will also be higher for webs from previously dried fiber than for ones from never-dried fiber.

## Hypotheses

Up to now, we have analyzed the factors that may lead to different water removal between previously dried fiber and never-dried fiber during the papermaking process. All of these factors are summarized in Figure 1.

Upon further analysis, it is found that these factors are all related to the irreversible swelling of fibers after drying. Although there are several theories to explain the mechanism of reduction in swelling, the most probable reason is the pore closure in cellulose fibers after drying. By NMR relaxation analysis, Haggkvist, et al. [63] found that during pore closure all pores are gradually closed and each pore passes through all pore sizes in the range of its largest size to

a state of complete or almost complete pore closure. Therefore, the reduction of pore size and reduction of pore volume are related to each other. After drying, the number of pores, the average pore size, and the total pore volume will all decrease.

The reasons why never-dried fiber is more difficult to dry can be classified into two categories: (1) higher moisture content after wet pressing, which will give a greater water load to the dryer and (2) reduced drying rate in the dryer. Thus, we can deduce the following two hypotheses to explain why never-dried fiber is more difficult to dry than previously dried fiber.

**Hypothesis 1.** *The decrease of pore size and pore volume in previously dried pulp will lead to a higher permeability and lower swelling. As a result, previously dried pulp will have a higher solids content than never-dried pulp after undergoing the same pressing.*

**Hypothesis 2.** *Compared to never-dried pulp, the decrease of pore size and pore volume in previously dried pulp will result in a higher drying rate in the late stages of the drying process.*

### SUGGESTED RESEARCH

The objectives of this suggested research are to determine why it is more difficult to remove water from never dried pulp than from previously dried pulp during the pressing and drying operation and to quantify the relative importance of both pressing and drying on this phenomenon. In order to achieve this goal, a series of appropriate experiments is suggested. A brief summary of the experimental approach is given in Table III and discussed in this section.

Table III. Overview of the experimental approach

No.	Experiment	Expected Outcome
1	Prepare never-dried pulp	prepare three different kinds of never-dried pulp properties of never-dried pulp
2	Prepare previously dried pulp	simulate previously dried baled pulp and recycled pulp by drying pulp from step 1 effect of drying history on pulp properties
3	Pressing	obtain the relationship between pore size (or pore volume, WRV) and sheet off wire solids content get the relationship between pore size (or pore volume, WRV) and sheet moisture content after pressing obtain the effect of wet pressing on pore size
4	Drying	obtain the relationship between pore size and drying rate obtain the relationship between pore size and critical moisture content obtain the effect of drying on pore size
5	Hypothesis testing	test hypotheses 1 and 2

### Prepare Never-dried Pulp

It is reported that the effect of drying on high-yield mechanical pulp fibers is minor because of the presence of ligno-hemicellulose gel in fiber walls that prevents any direct contact between cellulose surfaces during drying. On the other hand, low-yield chemical pulp fibers show a progressively greater loss in recovery of associated water with the extent of drying [60]. Some researchers also found that carboxyl groups contained in the pulp have an influence on the hornification of kraft pulp. Pulps with higher hemicellulose content may have a lower tendency to hornify [61]. However, if the hemicelluloses were removed prior to drying, the effect of drying on fiber properties (such as WRV, pore volume, swelling, bonding) were significantly increased [62].

Obviously, the effect of drying history on the fiber is related to its lignin and hemicellulose content, although the mechanism has not been resolved satisfactorily. From this consideration, three pulps with different amounts of lignin and hemicellulose (Table IV) will be used in the proposed experiments. In order to compare the experimental results, all the pulp will be prepared from the same wood chips.

Table IV. Pulp samples with different amounts of lignin and hemicellulose content

Pulp	Lignin content	Hemicellulose content
Bleached kraft pulp (BKP)	low	low
Thermomechanical pulp (TMP)	high	high
Holocellulose	low	high

### Prepare Previously Dried Pulp

From a literature review, it is found that increased drying temperature gives rise to reduced swelling. Treibër and Abrahamson [28] reported a considerable drop in fiber saturation when drying a dissolving pulp at 120°C compared to 25°C. On the other hand, wet pressing can also reduce the fiber swelling. Lindstrom and Carlsson [14] found the fall in WRV was around 15% for a refined unbleached kraft pulp after wet pressing.

Obviously, different drying and pressing histories will have some effect on fiber properties. In the paper industry, pulps with previous drying may come from recycled paper or baled market pulp. Pulp from recycled paper may have experienced a higher drying temperature and higher pressing pressure than that of baled market pulp. This may result in different dewatering properties between these two kinds of pulp. Therefore, we will simulate these two kinds of pulp and investigate the effect of different drying history on pulp dewatering properties.

### Pressing

Water removal by mechanical means in the press section is much less costly than evaporation in the dryers. An increased solids content after the press section of one percentage point reduces the energy consumption in the drying section by approximately 4%. The water removal during pressing is proportional to the product of pressure and time of application. In this experiment, we will use a high-speed press simulator to simulate the pressing process under different pressing pressure and machine speed. The pressing pressure will change from 200 psi to 800 psi and pressing time changes from 10ms to 20ms. By comparing the outgoing dryness of previously dried fiber and never-dried fiber webs, we can get the relationship between fiber pore size (or pore volume, WRV) and outgoing dryness and find the effect of drying on water removal during pressing.

### Drying

In this experiment, a drum dryer will be used to simulate the industrial drying process. Since the drying rate is greatly influenced by the temperature of cylinders and the critical solids content also increases with the drying temperature, different drying temperatures (105°C, 120°C, and 150°C) will be used in the experiment. It is expected that we can find the relationship between fiber pore size (or pore volume, WRV) and drying rate with this experiment.

## Test Hypotheses

Although we may find how drying history affects the dewatering during the pressing and drying process using the above experiments and obtain the relationship between fiber pore size (or pore volume, WRV) and its dewatering properties, it is possible that other factors caused by fiber drying (such as cellulose chain cleavage, cell wall reorganization, etc.) will also affect the dewatering properties. To use the results from the above experiments to test the hypotheses, more experiments are needed.

In order to test the hypotheses, a technique should be used to change the fiber pore size or swelling, but at the same time avoid any other unnecessary physical or chemical changes. It is found from the literature that pulp fibers exhibit a polyelectrolyte swelling behavior. When NaCl was added to bleached kraft pulp, very small changes in the WRV were found due to its low content of acidic groups. For holocellulose, however, a significant drop in WRV was found after a liquid exchange with 0.2M NaCl [14]. Taking advantage of these different properties between holocellulose and bleached kraft pulp, we can change the fiber swelling by NaCl treatment and compare its dewatering properties with that of the fiber without treatment.

## CONCLUDING REMARKS

We have attempted to bring together and assess the literature relevant to understanding the impact of pulp drying history on water removal and machine productivity. It is clear that previously dried fibers can result in greater productivity. One aspect not explicitly investigated, but of much practical importance, is a comparison between the use of pulps with different drying histories in the context of production of the same product (i.e., having the same physical properties targets). This could imply that the previously dried pulp would have to be refined more, causing a reduction in the productivity benefit.

It was not possible to quantitatively determine the relative importance of reduced water load to the dryer section and increased drying rate, although there seems to be evidence that the former effect is somewhat more important. A research approach was suggested that could lead to the desired quantitative information and to improved understanding of the phenomena.

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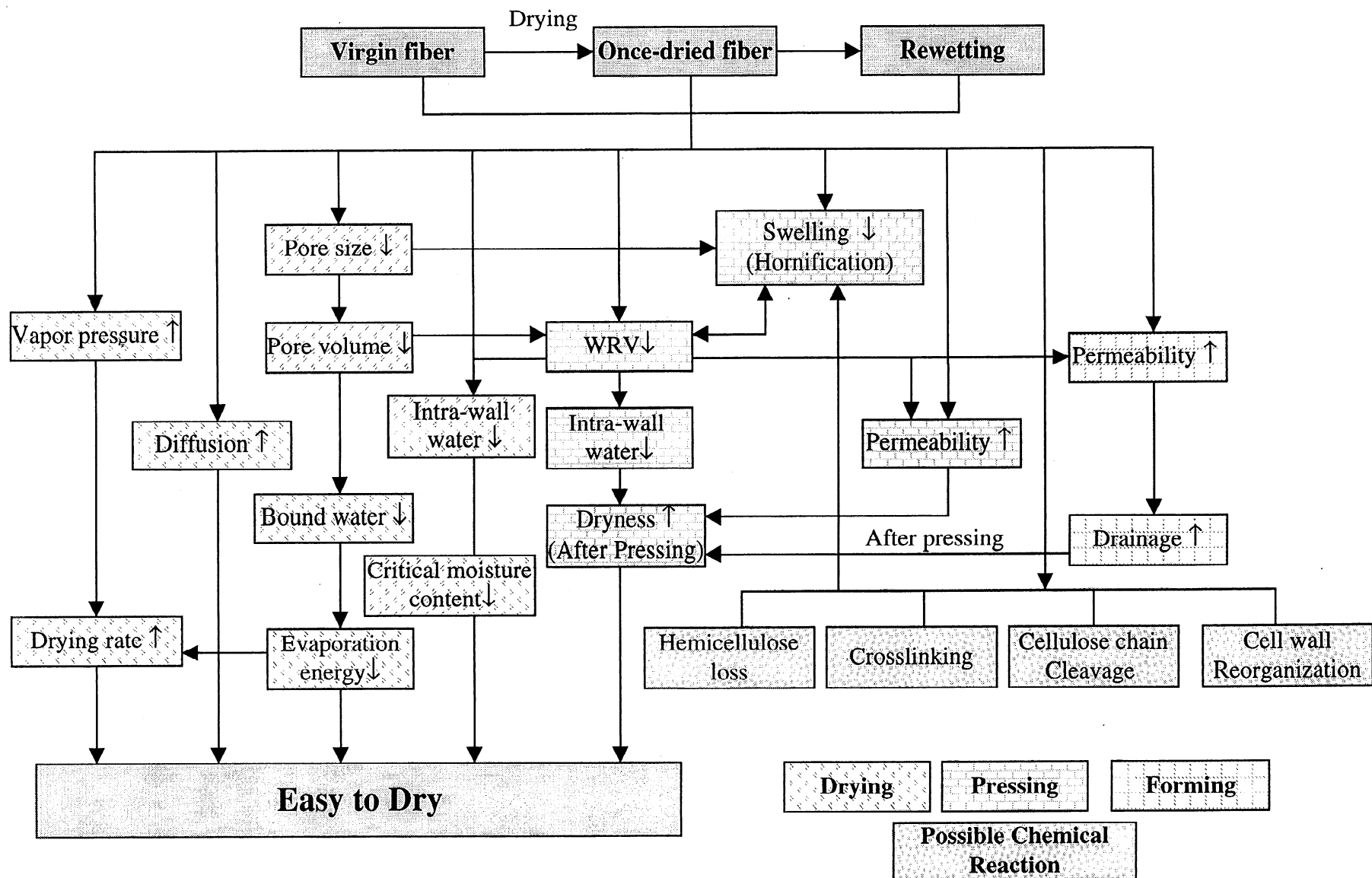


Figure 1. Problem Analysis diagram. ↑ or ↓ indicate the increasing or decreasing for once-dried fiber while comparing with virgin fiber at the same moisture.



